REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
03/31/2016	Technical Report (Quarterly)	01/01/2016 - 03/31/2016

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
A Hybrid Approach to Composite Damage and Failure Analysis Combining Synergistic Damage Mechanics and Peridynamics	
	5b. GRANT NUMBER N00014-16-1-2173
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Dr. Ramesh Talreja	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Texas A&M Engineering Experiment Station (TEES) 1470 William D. Fitch Parkway College Station, TX 77845	M1601473 / 505170-00001/2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Office of Naval Research 875 N. Randolph Street Suite 1425 Arlington, VA 22203-1995	ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The work performed in the first three-month period has been focused on Task 1.1 and Task 2.1 described in the project proposal. The activities related to Task 1.1 are a computational micromechanics failure analysis of a representative volume element containing disordered fiber distributions. Task 2.1 is concerned with damage evolution in a peridynamic model of poroelastic materials. Initial results for both tasks are reported and the ongoing work is outlined.

15. SUBJECT TERMS

Computational micromechanics, Cavitation induced cracking, Peridynamics, Porous media

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			William Nickerson
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	SAR	6	703-696-8485

Quarterly Progress Report, January 1 – March 31, 2016

A Hybrid Approach to Composite Damage and Failure Analysis Combining Synergistic Damage Mechanics and Peridynamics

Award Number N00014-16-1-2173

DOD – NAVY – Office of Naval Research

PI: Ramesh Talreja
Co-PI: Florin Bobaru

Executive Summary

The work performed in the first three-month period has been focused on Task 1.1 and Task 2.1 described in the project proposal. The activities related to Task 1.1 are a computational micromechanics failure analysis of a representative volume element containing disordered fiber distributions. Task 2.1 is concerned with damage evolution in a peridynamic model of poroelastic materials. Initial results for both tasks are reported and the ongoing work is outlined.

Task 1.1 Micro-level crack Initiation

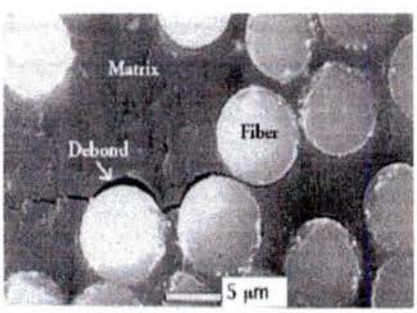
Background and motivation

Manufacturing of polymer matrix composites (PMCs) results in disordered fiber distributions and defects such as voids in the matrix. We focus in this task on the local stress states in the matrix that become triaxial under any remotely applied stresses resulting from the service environment in which a given composite structure operates. The local stress states are responsible for the precursor mechanisms that initiate cracks. This task studies the point-failure processes that become critical under favorable energy conditions. The two basic energy-driven processes are cavitation and shear-band formation in polymers. The former is governed by the dilatation energy density, while the latter requires energy of distortion for its initiation.

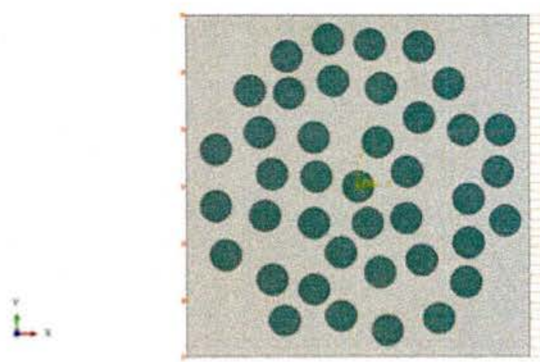
The work conducted in the reporting period has focused on cavitation, leading to micro-level crack initiation near fiber surfaces, i.e. fiber-matrix debonding. The remote loading considered in this work is tension normal to fibers (so-called transverse tension).

Approach and Results

Figure 1(a) shows an observed scenario in a PMC that is the subject of this study. The approach taken is to simulate the disordered fiber distribution using a two-point correlation function, as illustrated in Fig. 1 (b).



(a)



(b)

Fig. 1. (a) Fiber-matrix debonding observed in a unidirectional composite subjected to transverse tension (here, in the vertical direction). (b) Simulated region of disordered fiber distribution using a two-point correlation function.

Several realizations, such as that shown in Fig. 1 (b), were generated. The number of fibers used in each case was 40, based on previous studies concerning the size of a representative volume element (RVE). Each RVE realization was analyzed with a finite element model, where the local stress states in the matrix were calculated and were utilized in the failure analysis.

The failure analysis consisted of determining which of the two mechanisms (cavitation and shear-banding) are likely to initiate first. Figure 2 shows the dilatational and distortional energy density variations with the remote tensile strain. The zero strain corresponds to thermal cooldown.

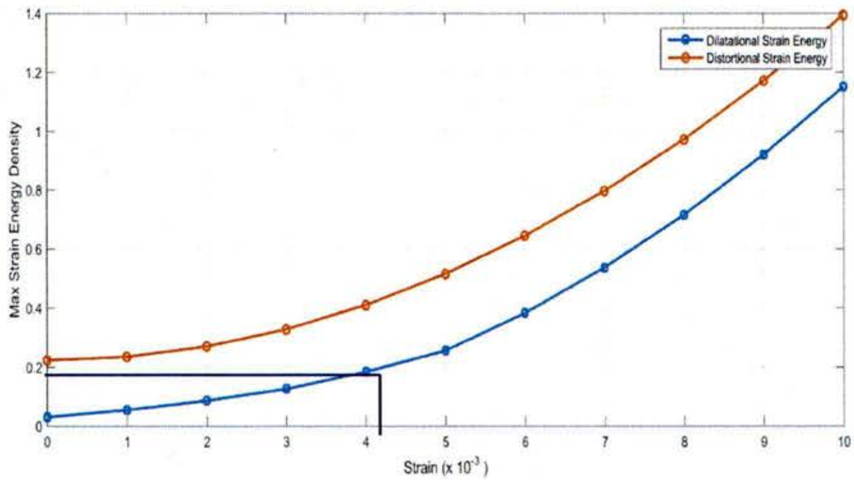


Figure 2. The variations with applied strain of the dilatational energy density (lower curve) and of the distortional energy density (upper curve). The criticality is reached at approximately 0.4% strain when the dilatational energy density reaches the experimentally determined critical value.

To validate whether the critical dilatational energy density represents hydrostatic tension, the three principal stresses are calculated and their pair-wise ratios are plotted in Fig. 3.

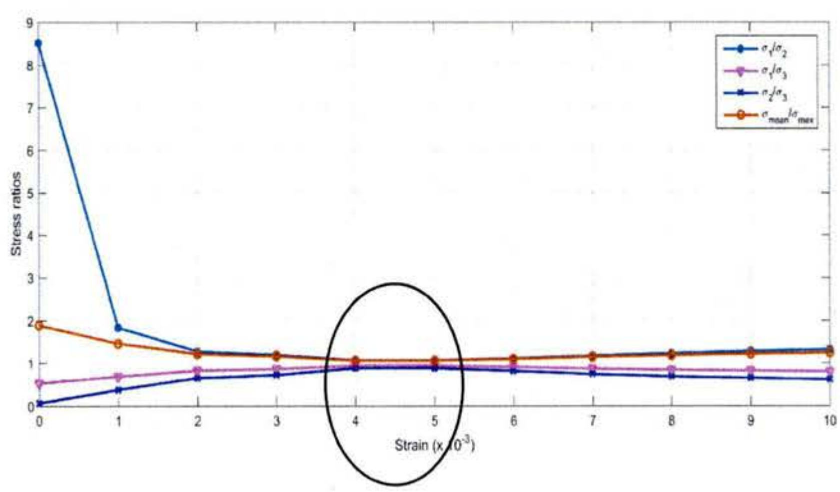


Figure 3. The pair-wise ratios of principal stresses and the ratio of the mean to max principal stress corresponding to the results in Fig. 2 are plotted. The most favorable range of applied strain to induce cavitation is circled.

The results shown in Fig.2 and Fig. 3 are for a glass-epoxy composite for which the critical dilatational energy density has been experimentally found to be at approximately 0.2 MPa.

Ongoing work

We will explore further the competition between the two plausible precursor mechanisms for micro-scale crack formation. The influence of constituent properties and fiber volume fraction appear to be important based on some results just obtained. For instance, the cavitation-induced fiber debonding could possibly occur during thermal cooldown before any mechanical strains are imposed. One example of this is shown in Fig. 4.

Other boundary conditions, such as combined transverse tension and in-plane shear are also in the plans. This will require going to 3-D RVEs.

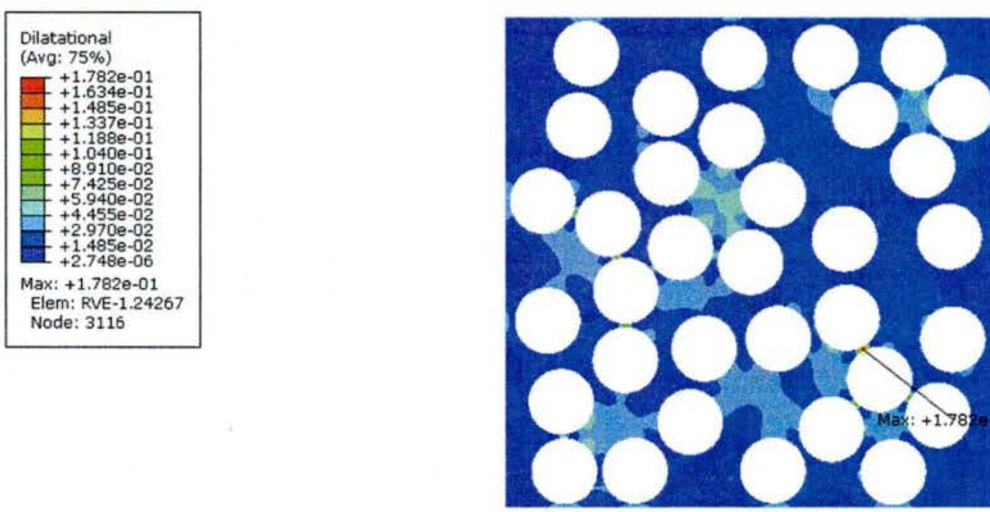


Figure 4. An RVE developing cavitation-induced fiber debonding on thermal cooldown. The site of possible fiber debonding is indicated by an arrow.

Task 2.1: Damage evolution in a peridynamic model of poroelastic materials.

Background and Motivation

In order to model the presence of pores and manufacturing defects, as well as the presence of microcracks generated during the stage I of damage in a composite, we have developed a peridynamic model in which pre-damage is distributed in the material system

according to some prescribed mean. As a first step in validating the model, we select a uniform random distribution of such pre-damage and test it for the case of an isotropic material. The subtask treated in this reporting period was the verification of the peridynamic model in terms of failure evolution in an isotropic porous material. We start first with materials with high porosity, like rock. The next step will be use this for materials with low porosity but high density of microcracks like those seen in the matrix of composites at the end of Stage I of damage. The particular distribution of such non-interacting cracks will be provided by the SDM analysis by Prof. Talreja's group.
The regime of interest here is the quasi-static or slow dynamics, for which we implemented a hybrid implicit-explicit solver. Over deformation regimes that do not result in growth of damage, the implicit solver allows taking large computational steps, while once damage growth begins, we automatically switch to an explicit solver to ensure that eventual dynamic characteristics of the fracture process are well accounted for.

Approach and Results

Porosity makes material softer and weaker. Many models have been proposed to predict the dependence between porosity and overall material properties, such as elastic modulus, facture toughness, thermal and electrical conductivities. Although these models can capture the relationship between apparent parameters and porosity values, these homogenization models are not able to reproduce the localization effects induced by pores/voids. For instance, in the compression test of porous rock (sandstone), a *process of damage accumulation* is observed before final failure. To capture the localization effects, we consider that porosity can be represented as peridynamic damage, defined by pre-breaking of peridynamic bonds. By randomly breaking some of the mechanical bonds connected with a peridynamic node, we can achieve a desired porosity.

We observed that this type of porosity created as equivalent damage, slows down wave propagation as expected. To verify the model, based on the computed wave propagation speed we extracted the apparent modulus for the material. The new peridynamic model for porous materials reproduces the apparent modulus measured in experiments over the entire range of porosities for which experimental results are available, from low porosity to very high porosity.

We validate this new peridynamic model on a compression test of porous rock (see Fig. 1). As shown in the right panel of Fig. 5, a porous rock is fixed at its left side and the right side is forced to move so that the rock is compressed horizontally. This is a displacement controlled loading condition, similar to what happens in an experiment. In our simulations, the rock fails when the right side displacement reaches 0.5 μm, corresponding to an overall strain of 0.05%. The peridynamic model captures the final damage pattern, which connects the notches via a shear-dominated crack. More importantly, the model predicts that damage starts to accumulate when the displacement reaches 0.3 μm. This damage accumulation process, also observed in experiments, cannot be obtained with homogenized models. The reason that it can be captured in the peridynamic model, is that randomly pre-damaged bonds make the model structurally heterogeneous, or micro-heterogeneous.

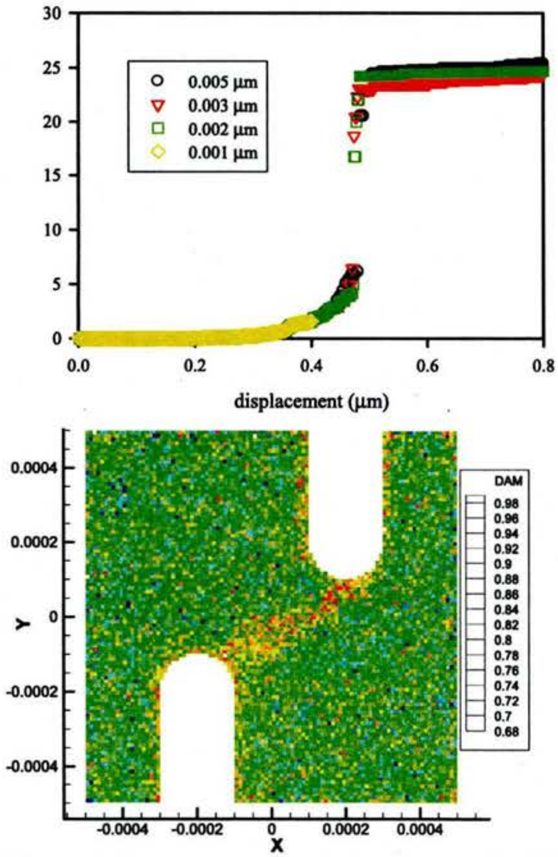


Figure 5. Damage accumulation before final failure. Left panel: the total damage evolution for different loading step size (the displacement increment at each step). Right panel: final damage pattern.

Ongoing work

The work reported above will be continued, in particular for anisotropic cases.